Integrated Hybrid Solar Energy for Efficient Green Hydrogen Production via Alkaline Water Electrolysis: A Research Framework

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Abstract: Alkaline water electrolysis (AWE) is one of the promising processes that could be used to produce green hydrogen using intermittent solar power. However, the study of the PV supply, heat recovery, dynamic operation and the durability of the PV stack are generally studied separately. In this paper, experimental and modelling studies are reviewed to create a research framework to integrate the use of useful solar heat with PV electricity in hot high irradiance conditions for AWE. Various evidence from modelling electrolyzer, direct PV coupling, PV/T heat recovery, part load and physics guided machine learning was taken into account. The results indicate that recovered heat could decrease the electricity load on the stack and alkaline system could be flexible enough to handle variable renewable energy. It is not clear how a controller is to respond to faster electrical responses and slower thermal/gas responses without accelerating deterioration of the components. The suggested scheme is based on irradiance and ambient temperature for the scheduling of current density and heat input, electrolyte flow, and operating mode. Feedback mechanisms between performance and condition monitoring are provided by the stack voltage, temperature, pressure, gas purity, hydrogen yield, and specific energy consumption, as well as by the voltage rise. A set of five test case hypotheses is provided to (partially) differentiate one electrical-only control and coordinated hybrid and health-aware controls. This paper is not intended to provide final performance results and serves only to provide the foundation for the experiments planned.

Keywords: *alkaline water electrolysis; hybrid solar energy; photovoltaic/thermal; dynamic operation; health-aware control.*

Introduction

Green hydrogen can be considered a transitional technology between renewable power generation and CES and other "hard to electrify" industrial processes. Alkaline water electrolysis (AWE) is one of the several approaches that are currently available and has matured to a stage of relatively widely distributed raw material and is available to scaly-up to larger deployments. Although the process of AWE seems relatively simple it is really an intertwined process with electrochemical, thermal, hydraulic and gas-separation-carrying processes. The cell voltage is influenced by reversible, activation, ohmic and mass-transfer components and several of these are influenced by changes in temperature or electrolyte concentration [1], [3], [6]. Therefore, using only a cost maximization approach at a particular instant can lead to other conditions such as cost or mechanical loads in the system.

This problem becomes more acute with the advent of solar coupling. Power matching between the PV source and the electrolyzer load can be very good, delivering high solar-to-hydrogen conversion efficiencies from direct PV-to-electrolyzer operation: in one concentrated PV/alkaline (CPV/A) demonstration, an efficiency of 16% was achieved [10]. Photovoltaic/thermal (PV/T) collectors add another valuable asset: the heat that is absorbed from the PV module preheats the process flow, and the photovoltaic cells are cooled. It is evident from this fact that the heat being rejected is a significant flow in one experimentally validated small scale study where 1,912 kWh was recovered in a year and 556.8 kWh was recovered in the form of PV electricity over the same period [4]. It is important to realize that it is not the heat that is being recovered, but rather the additional

supply of hydrogen and the corresponding reduction in the specific electrical energy demand, coupled with the satisfactory rate of component ageing that will result from coordinating both energy forms together.

The main one is, can coordinated use of solar electricity and useful heat increase hydrogen production from solar resources while maintaining stability and safety of AWE operation in conditions typical for the Sultanate of Oman? In this initial phase of the postdoctoral research, this research paper consolidates the relevant information, establishes the problem statement for the control part of the work and proposes some hypotheses that will be further verified in the experimental stage of the research.

Related Work

Stack polarization and thermal phenomena were addressed at the system level in early AWE models [1]. Subsequent studies confirmed the semi-empirical expression for the kilowatt scale units [3] and investigated the influence of the scientist variables temperature, pressure, electrolyte composition and current density on performance [6, 12]. Further, plant models included electrolytic circulation, gas separation, thermal inertia, and auxiliary loads [7] through this. In terms of controller design this evolution provides a good basis but the parameters are usually determined for the controller through the use of regulated power supplies, leaving the simultaneous variation of solar electricity input and available process heat unaccounted for in the models.

Studies on renewable coupling are performed on systems of a single electrical source and single electrolyzer as a coupled system. A power-matched concentrating photovoltaic system has been shown to have good solar-to-hydrogen efficiency [7, 10] and hybrid wind-PV sizing and dispatch strategies have been employed to optimize hydrogen production and storage [2]. The inclusion of a thermal dimension is made possible for PV/T experiments, where heat preheating for a process can be provided by cooling the PV module. A similar study was conducted in Bilbao [5] for the integration of heat recovered from a PV array and an electrolyzer to increase hydrogen production in the town of Antofagasta (Chile). While most of these studies look for annual energy values or the steady state thermal gain, they provide little information about energy use and heat distribution over repeated operating periods.

Transient studies show the inadequacy of steady state polarization data in understanding solar operation. In industrial-plant models, the electrical parameters change fast, whereas the stack temperature and gas inventory change much more slowly [7]. Part load experiments have also shown that power fluctuation not only has an impact on the stack but also on the balance of plant [8]. Tests performed on a 250-kW system found that start-up behavior, ramping characteristics and gas-management dynamics which cannot be observed in steady-state analysis [9]. Industrially, flexibility has to be considered in conjunction with efficiency, capital cost or service life [11] and also with the durability of the electrode and catalyst materials [13].

While machine-learning models provide a possible route to estimation of the internal states and prediction of short-term behavior, the data-driven approach may suffer from the loss of the physical-electrochemical limits. To circumvent this, Chen et al. [14] put forward a knowledge-integrated framework that takes physical information into consideration both for changing the input and for the structure of the model and for the validation process. The project has also addressed other related studies, such as probabilistic/AI-based reliability modeling for PEM electrolyzer [15] and modeling of electrode and membrane degradation in solar powered AWE [16] and operating variables optimization of PEM electrolyzer [17]. The next rational step would be to incorporate these concepts with the measured AWE data in a hot climate with two variable solar inputs: electricity and heat.

Key Contribution This research, which integrates these previously independent research lines in a unified supervisory control system, focuses on secure relations between control law design and modeling post-processing. The main thrusts of this study revolve around safe relations between the design of the control law

and the post-processing of the model. The responses of electrical, thermal, and gas are considered as separate inputs by solar electrics, and the different speeds of such subsystems are taken care of by the controller. It is aimed at increasing the hydrogen yield and specific energy consumption without surpassing limits of purity, temperature, pressure, and operating stress. The main constraints of the process will be captured by a physics-based dynamic model while the temporal learning model will estimate the residual behavior and uncertainty. The study directly addresses the integration gap, showing how, in various ways, it can be achieved through these key trends, as illustrated in Table 1.

Table 1. Evidence streams and the integration gap addressed by the proposed study.

Study	Focus	Evidence/strength	Unresolved need
[1], [3]	Steady-state and semi-empirical AWE models	Validated voltage–current and efficiency relationships	Limited representation of hybrid heat input and field intermittency
[2], [10]	Direct renewable-electric coupling	System matching and high solar-to-hydrogen potential	Thermal energy is not coordinated with stack health
[4], [5]	PV/T and waste-heat integration	Recovered heat and preheating can improve energy utilization	Mostly yield- or heat-focused; dynamic AWE control is unresolved
[7]–[9]	Plant dynamics, part load, and transients	Electrical, thermal, gas, and balance-of-plant responses are measurable	No unified solar-electric/solar-thermal supervisory policy
[11], [13]	Industrial needs and electrode durability	Efficiency, materials, scale-up, and lifetime are coupled	Degradation is rarely embedded in dispatch objectives
[14]	Knowledge-integrated machine learning	Physics can constrain data-driven monitoring	AWE-specific, hot-climate validation remains limited
This work	**Health-aware hybrid solar AWE**	**Links resources, control, states, yield, efficiency, and health**	**To be tested experimentally under Oman-like profiles**

Proposed research (Method) and research framework.

Focused evidence synthesis

In this conference paper we discussed the experiments and models mentioned in the first presentation, and crosschecked the bibliographic information on the experiments with the publishers' records. Studies meeting the following criteria were included: (1) evidence of AWE electrochemistry, (2) evidence of renewable power coupling, (3) evidence of useful-heat integration, (4) evidence of dynamic or part-load operation, or (5) evidence of condition-aware prediction & optimization. Original research article were given priority. Only a review and perspective paper was drawn upon for the purpose of the needs of industry and material related issues. Given that the studies chosen differ in scale, the system boundary, and in performance measures, the findings from the selected studies were synthesized through the focused narrative synthesis approach.

A system's boundary and measurable values.

The experimental boundary will include the photovoltaic source, re-cycled hot energy from the sun, conditioning equipment for electrical energy, alkaline stack, electrolyte circuit, gas separation equipment, and necessary auxiliaries. Irradiance, ambient temperature, PV power and stack temperature, current and voltage

of the PV module, battery thermal power, stack temperature and pressure, electrolyte concentration and flow, hydrogen flow and gas purity as long as available instrumentation. Performance will be reported based on hydrogen produced per day, specific energy consumption at the stack level and the system level (kWh kg-1 H2), solar-to-hydrogen efficiency, availability, voltage rise and cycling. Both stack and system boundaries are important since auxiliary electricity and heat from outside the system can have a distorting effect on comparisons between systems. Although Naniwadekar et al. [18] worked on solar drying and not electrolysis, their systems were monitored using IoT, and these were elements they considered as part of the thermal subsystem, providing an instrumental reference for monitoring the thermal subsystem.

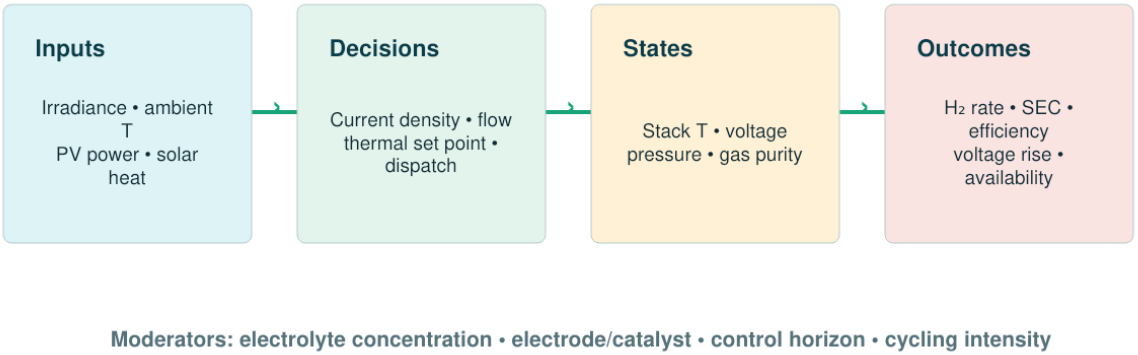


Figure 1. Conceptual linkage from solar inputs and control decisions to electrolyzer states and measurable outcomes.

Dynamic model, control cases, and validation

The system governing stack temperature and gas inventory will be governed by balances, while the semi-empirical model of polarization will be developed and combined with the together in the proposed grey-box model. The parameters will be estimated from the tests conducted at controlled current, temperature, electrolyte levels. A variety of power profiles are then used to test the model, which include hot-high-irradiance day profiles that are not used for the model to be optimized with during the parameter fitting process. The following three operating cases are tested: B1, rule based electrical only mode; B2, coordinated photovoltaic and thermal control, and B3, health-aware multi-objective control. For B3, the controller will compare the specific energy consumed, temperature excursions, and risk of low load purity, rapid cycling, and voltage rise during a continuous event for hydrogen production.

The physics model will generate meaningful state estimation and enforce mass and energy constraints along with operating constraints. Only to estimate the remaining systematic error terms in the physical model will be used with a temporal machine-learning model. Performance will be evaluated on unseen profiles, as well as an agreement to mass and energy balances, using the following metrics: mean absolute error, root-mean-square error, prediction-interval calibration. If these are repeated blocks of profiles, then paired comparisons between B1, B2, and B3 may be made. Effect sizes and 95% confidence intervals will be included along with significance testing. A sensor study will be done before the confirmatory experiments to establish the baseline level of error; minimum effect that might be considered of practical significance will be determined after the baseline but prior to the confirmatory experiments.

Testable Hypotheses

H1—Thermal assistance: At matched hydrogen production and boundary conditions, useful solar preheating will reduce stack-specific electrical energy relative to electrical-only operation.

H2—Coordinated yield: Across matched irradiance profiles, coordinated photovoltaic/thermal control will increase daily hydrogen yield and solar-to-hydrogen efficiency relative to B1 without violating temperature, pressure, or purity limits.

H3—Dynamic prediction: The coupled electrical–thermal–gas model will predict stack voltage, temperature, and hydrogen flow on unseen variable-power profiles within preregistered error limits.

H4—Physics-informed learning: A physics-constrained temporal residual model will outperform static empirical and unconstrained data-driven baselines for short-horizon performance and voltage-rise prediction while preserving balance consistency.

H5—Health-aware dispatch: Compared with yield-first coordinated control, B3 will reduce rapid cycling, temperature excursions, and normalized voltage-rise exposure without a practically significant loss of daily hydrogen yield.

Discussion

The studies selected collectively form a reasonable basis for the five hypotheses, but do not guarantee that all five will be true of an integrated system. Increasing the stack temperature increases the reaction rate and improves the ionic conductivity, but the advantages of this may be offsetting by heat-transfer losses, decreasing PV efficiency at high module temperatures, gas crossover, corrosion, limitations of the separator, and increased auxiliary power consumption. So for the purposes of this, recovered heat will only count as useful if it is associated with a measurable change in the system performance, and traverses the defined system boundary. Heat recovery should be considered more as a complement to the electrical work of electrolysis.

The controller needs to take the varying response times that can exist throughout the plant into consideration as well. While operating conditions such as stack temperature and gas inventory will materially influence current, they will also be changing more slowly and people can make the adjustment almost immediately. Opting for sizing up the system based on the sun's power output when it is most productive might seem to be a viable solution, but could just lead to temperature overshoot, contamination of the gases or to extra auxiliary operation. STIRs can aid in decisions regarding ramping, maintaining, or shutting down the stack; storage, bypass, or supply of heat; and when to decide to cease all activity at the stack.

Oman is not just an easy place in which to conduct the proposed experiments. Although it is found to have high solar irradiance, it is demonstrated that high ambient temperature decreases the PV efficiency and hence less cooling space for the PV stack. The dependence of measured irradiance and the power supplied to the electrolyzer may also change as a result of dust and seasonal changes. For this reason, for such circumstances as that of temperate climates, it is necessary to use local operating profiles for determining if conditions are acceptable for maintaining the reliability of a controller developed with tropical-climate data. Initial results will be valid only for the given stack, balance of plant, electrolyte and control horizon and any performance claims for larger scale applications should be validated separately.

There are several important caveats to this paper. First, it's a focused narrative review instead of an extensive systematic review. Secondly, the planned experiments have not yet been tested to confirm the proposed model. Third, voltage rise is taken as a health indicator in stacks first of all, but it doesn't represent all degradation mechanisms. A longer test should thus be accompanied by periodic measurements of polarization [12] and periodic checks of the purity of the gases [13] as well as characterization of the material [16]. Accepting these drawbacks defines what evidence will be required prior to making the conclusions about the efficiency or service life of the system.

Conclusions

In addition to research published so far showing solar-electrical AWE operation, useful-heat recovery, dynamic modelling and physics-guided learning, these features have not yet been sufficiently investigated in combination. One of the main shortcomings is lack of coordinated control considering, at the same time, electrical, thermal, gas and stack-health behavior under realistic solar variation. These five hypotheses propose measurements as an equivalent way of dealing with this gap, leading to measurable Comparisons of energy demand, hydrogen yield, prediction accuracy, operating stress and safety limits.The experimental work will start

with baseline testing of the controlled rate, and then be followed up with matched- profile comparisons for the electrical-only, coordinated hybrid, and health-aware control styles.

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